A Survey on Virtual Reality for Individuals with Autism Spectrum Disorder: Design Considerations

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Abstract—In this article, state of the art on virtual reality (VR) for individuals with autism spectrum disorder (ASD) with a focus on training/targeted intervention is discussed and reflected upon to explore areas for more future benefits. We present advantages of VR for individuals with ASD. We identify challenges and design issues for future training applications regarding individuals with ASD. We discuss and present design guidelines accumulated in the literature so far, mostly based on observations in user studies exploring the usefulness of VR as a training tool for individuals with ASD, with a systematic literature review. We present and apply a new taxonomy that classifies previous VR works on training individuals with ASD according to immersive and regular (non-immersive) VR systems and types of social, life and safety skills based on a systematic literature review. We explore the common design considerations of the previous VR studies for training individuals with ASD. Finally, based on the systematic literature reviews, we identify key gaps in the research on this topic and present future research considerations.

Index Terms—Assistive technology, user centered design, virtual reality, autism spectrum disorder, design considerations, training, targeted intervention

1 Introduction

Autism Spectrum Disorder (ASD) is a cognitive disorder that affects individuals throughout their lives. Main deficits associated with this disorder are: social interaction, communication, repetitive behaviors and adherence to routines [1]. Causes of autism aren't currently known. Autism is a spectrum based disorder. Individuals with ASD can be diagnosed as high, medium or low functioning based on their characteristics and impairments [2]. Although once considered a rare disorder, research indicates increases in the number of individuals with ASD in recent years with an estimation of 1 in 68 children [3], [4]. Several possible reasons have been argued for this increase such as increased awareness and lower threshold for diagnosis, and expanded definition of ASD. Although the underlying reasons might not be clear, the increasing number of individuals with ASD motivated development of several technological tools for assisting and training individuals with ASD, VR being one of the most popular among them.

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Manuscript received 14 May 2016; revised 5 July 2017; accepted 27 July 2017. Date of publication 15 Aug. 2017; date of current version 18 June 2018.
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For information on obtaining reprints of this article, please send e-mail to: reprints@ieee.org, and reference the Digital Object Identifier below.
Digital Object Identifier no. 10.1109/TLT.2017.2739747

Since autism is a wide spectrum disorder, it is difficult to characterize individuals with a single stereotype. Each individual may have different characteristics or different combinations of characteristics. However, some deficits are commonly observed in individuals with ASD [1], [5], [6], [7], [8], [9], [10], [11], [12], [13], [14], [15], [16], [17], [18], [19], [20], [21]. These deficits are in: • Cognitive and intellectual abilities • Sensory processing • Language and gestures • Reciprocal conversation • Movement and motor skills • Eye contact • Imagination, abstract and symbolic play • Mental simulation • Perception • Affect and empathy • Problem solving skills • Executive functions • Responses to sensory stimulation • Adaptation to changes • Generalization of learnt skills • Anxiety management • Cooperative working • Managing phobias/fears such as loud noises, dogs, thunderstorm and vacuum cleaners • Distinguishing between important and unimportant events/aspects.

On the other hand, individuals with ASD are stated to have an affinity to technology and a strong visual memory. Some individuals may have extraordinary abilities in one specific area such as mathematical calculations and musical abilities. These rare individuals are referred to as autistic savants [22].

Due to these characteristics, training plays an important role for individuals with ASD. Suggested real world training methods for individuals with ASD emphasize the benefits of visual assistance [23], [24], [25], [26]. Visual cues have been thought to aid significantly in comprehension of individuals with ASD [27], [28], [29]. Using a simple picture with a few descriptive words is suggested as a good practice. Activity cards, instructions, cue cards and environmental categorizations are prepared with this technique and have been used prevalently in training individuals with ASD, especially children, for a long time. This is mainly due to this population's being characterized as generally having a strong visual memory and difficulties in language comprehension. Hence, simple pictures that are relevant to the context of the instructions and tasks play an important role in training individuals with ASD. Comic strips with brief drawings are also used to train on social contexts such as conversations between two people [30].

Video modeling is also used as another method for training and teaching [25], [26], [31], [32], [33], [34] people with ASD. This method is composed of a video of an individual who models the task or behavior that is to be taught. Individuals with ASD can also be videotaped and later review and engage in reflection trainers. It is thought that individuals with ASD prefer video interaction due to an often-seen characteristic of feeling uncomfortable with social interactions involving real people.

Some technological tools have also been utilized in training of individuals with ASD such as computers, mobile and tablet devices, especially in classrooms of ASD specific schools and at some job training programs [26], [35], [36].

Virtual reality (VR) aims at immersing users so that they think that they are in a virtual environment. Virtual reality is defined in [37] as "a model of reality with which a human can interact, getting information from the model by ordinary human senses such as sight, sound, and touch and/or controlling the model using ordinary human actions such as position." VR is distinguished from other computer technologies mainly by the high level of interaction and immersion it offers. Immersion is the sense of being physically there in the virtual environment. Immersion can increase effectiveness of learning by eliminating environmental distractions and helping individuals maintain focus [38]. High degree of interaction in VR is provided via motion tracking and utilizing movements of the user into possible interactions in the virtual environments.

There are mainly three types of VR systems: wearable Head Mounted Displays (HMDs), projection systems that project the virtual worlds onto the environments and desktop computer systems [39]. A head mounted display is a visual display that covers the eyes of the user. Projection systems are often called cave automatic virtual environments (CAVEs), in which seamless projections of the virtual world are made onto walls, ceiling and floor of a room or panels surrounding the user [37]. Immersive VR is a type of VR in which the users are completely surrounded by the virtual environment as if they stepped inside the virtual world. This is achieved by means of a HMD or CAVE projections and some form of motion tracking.

VR has been becoming a popular training, rehabilitation and intervention tool for individuals with ASD in recent years. Although most of the studies so far were evaluated with small groups of participants and provide weak evidence individually, in aggregate, these studies show the promising nature of VR as a training tool for individuals with ASD.

Early studies concentrated on the acceptance of VR for individuals with ASD and many confirmed that individuals perceived VR positively and accepted it [11], [12], [40], [41]. Recently, with the release of head mounted displays that offer more immersive and richer experiences, the applicability of this acceptance found out by early studies remained questionable. With this in mind, Newbutt et al. investigated the acceptance of the new generation highly immersive Oculus Rift^{TM} head mounted display [42] and found out that individuals with ASD accepted this HMD as well, independent of their levels of ASD or IQ.

Several studies indicate that VR provides enriched learning and training experiences [43], [44], [45], [46], [47], [48], [49]. Usage of VR in training and rehabilitation is prevalent because the human brain (neurotypical or otherwise) excels at learning with visual, auditory and tactile senses simultaneously [50]. Individuals with ASD are especially thought to benefit from this due to their attribution to strong visual memory. Individuals with ASD are characterized to learn better when presented with visual spatial information, which can be easily achieved with VR [29].

VR training offers several advantages that play to the strengths of individuals with ASD [11], [20], [40], [41], [47], [51], [52]. While being well-aligned to individuals with high functioning autism, these advantages may not align so well to low-functioning people with autism. These key advantages of VR training are: • Practicing in a safe environment • Ability to control and gradually increase task complexity • Active participation within the virtual world • Reinforcement through repetition • Creation of alternative realistic scenarios that facilitate easier generalization of concepts by variation • Customization of tasks and scenarios to cater to the wide spectrum • Real time alteration of properties • Decreased stress because of being able to independently interact with the system • Highly structured training and predictability • Clear boundaries to the tasks • High level of control on the provided stimuli • Increased focus by isolation from the surroundings in real world • Visualization of abstract concepts • Real time prompts • Immediate feedback • No severe, real-life consequences of mistakes • Automated data collection and replaying scenes for reflection • Automated assessment and reporting • Feeling more comfortable in stable/unchanging environments • No or minimized human interaction • Being highly visual based, exploiting their attribution to strong visual memory • Being appealing to this technology savvy population.

The National Autistic Society stated positive opinions on effective use of VR for ASD training since VR offers an environment in which people with ASD can feel comfortable. They affirmed the potential for successful use of VR in training individuals with ASD, especially in life and social skills [53].

There are several studies showing successful transfer of skills learned in VR to real life for neurotypical people [54], [55], [56], [57], [58]. There has been debate in early days of VR technology on whether VR could successfully provide generalization and transfer of learned skills for individuals with ASD, since this population is characterized to be likely to have some generalization deficits in real life [59], [60]. As an example, some individuals with ASD may have trouble in generalizing something learned at school into another setting such as home or mall. By contrast, several studies reported results that indicate successful generalization and transfer rates from virtual worlds to real life for skills trained with VR [12], [25], [41], [61], [62], [63], [64], [65], [66], [67], [42]. However, individuals with ASD may need more careful design of skill training due to their individual characteristics. Providing structured training that would encourage generalization of skills with several training sessions in different scenarios and environments might help in better transfer and generalization of skills.

Our two aims in this paper are as follows: (1) To find out if there are established guidelines for designing virtual reality applications for individuals with autism. To do so, we performed a systematic literature review to find out the design guidelines and considerations regarding virtual reality for individuals with ASD. (2) To find out the common characteristics of the previous virtual reality studies that aimed to train (or provide targeted intervention to) individuals with ASD. We performed a systematic literature review for this as well. Our research questions can be stated as follows: • Are there well-established guidelines in the literature for design and development of virtual reality applications for individuals with autism? • What are the common characteristics of virtual reality systems in the literature that aim to train individuals with autism on some skills?

Our main contributions in this paper can be summarized as follows: • Good principles for traditional training of individuals with ASD. • Predicted advantages of VR for individuals with ASD. • Systematic literature review on the design considerations for virtual reality systems targeting individuals with ASD. • Systematic literature review on virtual reality systems for training/targeted intervention of individuals with ASD that led to the common choices made in these studies. • A new taxonomy of the previous studies based on the VR system and skill type. • Future research considerations in the area of virtual reality for individuals with ASD based on the results of the literature reviews.

The rest of the paper is organized as follows: In Section 2, we review the challenges and design issues that are related to virtual reality systems for individual with ASD. In Section 3, we present a systematic literature review on design principles for virtual reality systems targeting individuals with ASD. In Section 4, we present and discuss a systematic literature review on virtual reality systems for training/targeted intervention of individuals with ASD and we offer a new taxonomy. In Section 5, we discuss the future research considerations based on the literature reviews. Finally, in Section 6, we conclude the paper.

2 Challenges and Design Issues

For traditional forms of therapy, interventions and support for individuals with ASD, there are several resources on best practices [26], [28], [29], [68], [69]. These resources were mostly prepared for schools and families; not for developing computer technologies. However, some practices can be applied to the use of computer technologies as well. Some of the key design guidelines for training individuals with ASD in real life are presented below: • Providing realistic stimuli that are relevant to the scope of the training task • Providing highly structured, organized and systematic content and learning environment • Establishing routines and following them • Providing warnings before changes to routines in the form of visual cues or other assistive methods • Customization of programs according to needs of the individuals in this wide spectrum • Providing flexibility and alternative methods in teaching • Providing clear goals • Providing a clear list of expectations • Using brief language and short sentences to avoid a shift in attention after a few sentences • Avoiding use of irony and other abstract concepts; using literal language • Highlighting key words • Giving concrete examples relevant to the context and avoiding direct teaching of information • Making connections to the previous and other content areas for easier generalization of the learned material • Giving instructions for a sufficient duration, not for a short amount of time • Favoring simplicity in all forms of information presentation • Removing unnecessary complex information of all forms since it may cause distraction • Providing alternative methods of communication instead of verbal such as true/false cards or drawings • Allowing for repetition of tasks for learning • Chunking longer activities in small segments of around 15 minutes • Encouraging use of technology for tasks such as writing and drawing since users feel more comfortable with computer interaction than human interaction.

Although there is an established agreement on good design principles for training individuals with ASD in real life, this is not the case with VR training. There is a gap between autism researchers who are experts in needs and preferences of individuals with ASD, and computer scientists who develop VR systems for individuals with ASD. Hence, while designing such systems for effective training, several questions may arise such as: What color schemes should be used? What kinds of presentation methods work better? Should the environment be cartoon-like or realistic? How crowded should the environment be? Would dynamic objects degrade focus or prepare them better for real world? What is the limit until dynamic objects cause distraction? Should real voice recordings or computer generated voice be used?

There have been endeavors to address this gap. Brosnan et al. reflected upon the effects of participatory design for technologies targeting individuals with ASD and pointed out that although participatory design is a promising tool, many questions and challenges remain in its effective use [70]. Parsons et al. utilized a collaboration with school practitioners in co-creating digital stories for an innovative tool for individuals with ASD [71]. The researchers stated that active participation of teachers enabled them to better critique the technological tool and improved the content with teacher's experiences and views. Parsons and Cobb reflected on including stakeholders of children with ASD and their children in the design process of an assistive technological tool to support social conversation and collaboration [72]. Although involving stakeholders improves the outcome, the authors mention the complexity of the processes in large scale multi-disciplinary projects targeting special populations such as ASD. All these endeavors emphasize the importance of inclusive design while pointing out the challenges that arise from the unknowns and the gaps between the different parties involved and the need for more structured approaches and well-established guidelines for design.

3 Design Guidelines and Considerations for VR Applications for Individuals with ASD

Many previous literature review papers pointed out that well established design guidelines for computer based

TABLE 1
Observation Based Design Guidelines and Considerations That Have Been Shared by Three or More Previous Works on Using VR for Training Individuals with ASD

Design Guideline/Consideration	References	
Providing structure and routine in training	[20], [68], [74], [78], [81], [84], [86], [99]	Task Design
Following an inclusive design with children, parents and other parties	[70], [71], [72], [80], [91], [92] [94], [98], [101], [103]	
Making the users feel in control	[68], [78], [80], [83]	
Utilizing the ability for attention to detail and visual memory	[20], [68], [78], [84]	
Providing real time positive feedback	[48], [74], [86], [101]	
Designing real and meaningful experiences with a link to real world	[20], [83], [86], [100]	
Utilizing a rewarding mechanism of sensory elements	[78], [94], [99], [102]	
Allowing for repetition in practicing the learned tasks	[46], [74], [81], [84]	
Allowing the users to customize the virtual world	[80], [97], [98], [104], [105]	
Utilizing gradual increase of difficulty	[46], [83], [100]	
Designing short training sessions with breaks	[74], [84], [100]	
Using animated cartoonish non-human virtual characters as tutors for children	[52], [83], [86], [87], [96], [104]	Information Presentation
Avoiding sudden loud sounds	[68], [74], [78], [79]	
Using simplified interfaces and graphics	[86], [88], [89], [90]	
Using 3D animations to attract attention and increase motivation	[48], [82], [86], [91]	
Using color, shape or movement to attract attention	[74], [83], [84], [94]	
Presenting clutter free scenes	[83], [86], [92]	
Providing clear foreground background differentiation	[86], [92], [93]	
Using simple and intuitive controlling inputs with a few buttons	[48], [52], [74], [83], [100], [107], [112]	VR System
Using less tiring input devices	[74], [92], [100], [112]	
Offering variety in tasks, information presentation and interactions	[86], [99], [100]	

training applications for individuals with ASD did not exist [73], [74], [75]. Several individual studies so far mentioned the difficulty arising from the unknowns in design considerations for this specific population. Some previous studies with small sample sizes included lessons learned, statements of participants on their preferences and observations of the researchers, practitioners, teachers and family members, which will be mentioned in more details and individually referenced in this section. However, these observations were not based on comparative user studies or statistical data. Furthermore, design considerations that have been reported so far were heavily dependent on the context of the tasks, characteristics and preferences of the small groups of participants and other conditions of the study.

To find out if there are well established guidelines in the literature for designing virtual reality systems for individuals with ASD, we performed a systematic literature review on this topic. This section reviews the existing design considerations derived in the previous exploratory studies. For the systematic literature review, the guidelines shared by Kitchenham et al. [76] were followed. However, since the design considerations that were found were only shared observations and were not the main focus of the studies that were confirmed with comparative statistical experiments, the studies that included the design considerations were not scored. Instead, the guidelines that were shared by many studies (more than three) were shared in Table 1, which will be revisited later. We included all studies that are related to virtual reality and autism in this search without any year or subtopic restriction (such as entertainment and educational applications). Our searching sources included the seven electronic sources that were classified as of relevance to software engineers by Brereton et al. [77] and some additional ones that included publications related to our topic of interest: • IEEE Xplore • ACM Digital Library • Google Scholar • Inspec • Science Direct • El Compendex • Springer Link • Elsevier • NCBI • SAGE Journals.

Since virtual reality is a fairly new area that emerged in the recent decades, we performed our search on electronic sources. To address the gray literature and eliminate publication bias, we included the Internet, works in progress and posters into our search. The following criteria were used for the search:

Inclusion Criteria. • Any publication related to virtual reality and individuals with ASD.

Exclusion Criteria. • Publications in a language other than English. • Self-publications (due to conflict of interest).

Search Strings. Virtual reality AND autism

Abbreviations/Synonyms. VR, ASD, Asperger's

Reference Manager. EndNote

All studies that were found were read in the following order: title, abstract, and main body (if the study was relevant). The references of these studies were also checked and included in the search, if relevant. Then, the design considerations were extracted from the studies and were synthesized in a table format with the criteria of being mentioned in at least three studies. Most of the existing studies were designed for children with ASD although some of the studies encompassed adolescents and adults with ASD.

Design considerations in previous works were clustered into three main categories based on the frequency of mentioning: methods of information presentation, task design and VR system.

3.1 Methods of Information Presentation

Sound. Avoiding sudden loud sounds have been advised by several studies [68], [74], [78], [79]. Some studies suggested that background sounds in VR applications may be annoying, even if they are natural and in relation to the context of the task [80], [81]. They suggested providing optional sound with volume control. On the contrary, another study observed that sound effects increased the motivation of the participants [82]. Verbal instructions for tasks also did not work well, in line with common ASD deficits in processing verbal information [83], [84]. However, when complemented with other informational methods or in comparison to providing no instructions, verbal instructions of tasks provided better understanding [85], [86], [87].

Text. Guidelines are unclear in regards to text. In one paper, the authors recommend using only written instructions in virtual reality applications [81]. On the other hand, another study noted increased motivation of users when written cues were provided [82].

Visual. In one study, simplified graphics in facial expressions provided more effective processing of information [88], [89]. Another study concurs, favoring less detailed faces [90]. In [86], the importance of having simplified graphics was emphasized. However, in other studies participants appeared to perceive more detailed virtual avatars as closer to real humans [89], [91]. They were perceived more positively by the participants and had an increased sense of presence.

Clutter also appears to have an effect in VR applications for people with ASD. Scenes with little clutter worked better [83], [86], [92]. For example, when there were less objects to collide with in the virtual world, users with ASD navigated the environment more easily. Using a limited number of drawings was also advised in order not to overwhelm the users [68], [78]. Likewise, clear differentiation between foreground and background was reported to work better in terms of comfortable viewing and understanding the content of the visuals [86], [92], [93]. With respect to color, previous work suggested using mild colors over bright colors.

Many studies emphasized the affinity and attention of individuals with ASD to visual presentations. Large, colorful and spinning objects attracted a lot of attention from participants. The users gave great attention to physical details of objects such as color, shape and movement [74], [83], [84], [94]. Space theme was stated as a common preference by families of children with ASD [95]. Based on study observations and advice from practitioners working with children with ASD, [48] recommends using visual symbol cards with accompanying verbal explanations.

Animation. 3D animations were reported to attract attention and increase motivation of participants with ASD [48], [82], [86], [91]. Movement by animation helped attract attention and put focus on a desired area. Animated feedback was also valuable in maintaining interest of children. However, highly engaging objects with dynamic sensory properties such as movement and shininess may detract the user from tasks [94]. Hence, the number of interactive objects in a scene is thought to be crucial in controlling the pace and excitement, with fewer objects and less unnecessary dynamism was stated to work better for individuals with ASD in terms of concentration, based on the observations of the researchers [74], [94].

Tutorial. For VR tutorials, using a virtual teacher was reported to work well for individuals with ASD in some studies [52], [83], [86]. Animated animal characters such as dogs were observed to increase motivation better than human characters in some studies, perhaps because individuals with ASD often feel discomfort in interactions with real humans. Instead of utilizing virtual human teachers to give users feedback and talk about correct or incorrect actions taken, using alternative characters who teach such as dogs and robots was suggested as a better design principle for children with ASD [52], [83], [86], [87], [96]. Children were reported to perform better when a virtual character first demonstrated the requested task as a role model [83], [97]. Also, children in the study learned best when a tutorial was showed twice [83].

Using images and animated avatars with accompanying narrations and speech in VR was reported to work well for tutorials in [86], [87]. Video was observed to be confusing as a tutoring method and the use of simple images was suggested in [79]. From another point of view, video based explanations were slightly favored by participants over cartoonish avatar-based explanations in [98].

Since attention can be short and shifted easily, restricting control in crucial training scenes was reported to work better for maintaining focus on a desired element [83].

An accompanying facilitator who provides physical assistance during training was suggested in [89], [92]. Although its effectiveness is unknown, we observed that this method was used by most of the studies mentioned in this paper.

3.2 Task Design

Exploiting ASD Characteristics. Many studies mentioned the importance of providing structure and routine, since these align with the characteristics of the ASD population. Providing consistency throughout all levels, so that rules and relationships are the same, was also suggested. Likewise, providing clear goals and objectives were stated to be very important in training individuals with ASD [20], [68], [74], [78], [81], [84], [86], [99]. Several studies agree on the importance of utilizing the ability of individuals with ASD for attention to detail and their strong visual memory in task designs and VR experiences [20], [68], [78], [84].

Children with Autism are stated to share common interest areas such as space, racing cars and technological tools according to their families [95]. Leveraging these special interests in the developed tools such as providing the users a selection of popular themes is suggested as a good design consideration, which would increase motivation of children.

Making the users feel in control was also emphasized as a good design principle by some studies [68], [78], [80], [83]. As an example, authors shared how penalties that took control away from the participants, such as moving back in the flow of the game or being exposed to a black screen for more than five seconds, created irritation. Vastness of the virtual worlds was also found to be irritating by individuals with ASD. These findings can be linked to the affinity of individuals with ASD to being in controllable, predictable situations.

Repetition of the learnt tasks was observed to provide better training, suggestively due to rote memory skills of individuals with ASD [46], [74], [81], [84]. To facilitate this, randomness in tasks was suggested since the users with ASD were observed to repeat the correct way over and over once learned [46], [81]. Using short sessions was advised in order not to overload the participants since individuals with ASD are characterized to have short attention spans [74], [84], [100]. Giving multiple stimuli concurrently was stated to be overwhelming and better avoided [86], [96]. Engagement with tasks decreased the repetitive behaviors in participants, which is a commonly seen characteristic of ASD [92].

Task Complexity. Gradual increase of difficulty in VR tasks was observed to work better in training individuals with ASD [46], [83], [100]. Increasing environmental VR elements such as crowdedness, dynamism and sounds gradually was also advised to avoid overwhelming users and provide room for adjustment. Breaking instructions and tasks to be performed down was stated to work better in [83] and [86]. Providing unachievable and daunting goals was found to be important for not breaking the motivation of the participants in [99] and [86].

Feedback. Real time feedback also appears to be important. Researchers observed that positive feedback given after performed tasks provided motivation in participants [48], [74], [86], [101]. In one study, progress tracking with a tool such as a score bar or a task counter provided a means of tracking and comfort for individuals with ASD [83]. However, another study suggested avoidance from competitive elements such as scores as they appeared to elicit negative feelings from users [81].

As stated previously, individuals with ASD are stated to show interest in animations. An experience in this regards on highlighting negative actions with animations was shared in [83]. The researchers stated that when they used animations to highlight negative actions, this did not provide learning for the users but provided enjoyment in watching these animated feedbacks (according to the observations of the researchers). As an alternative to animated feedbacks, the researchers found out that giving a black screen after a negative action for a short amount of time (one or two seconds) worked better in terms of learning. However, keeping the black screen duration long resulted in a feeling of loss of control in the participants with ASD.

Rewards, especially when mapped to sensory interests such as attractive movement, colors and shapes, was motivating for individuals with ASD in several studies [78], [94], [99], [102]. Statements of failure were reported to make users with ASD anxious. Encouraging words were advised to be used even in situations where feedback is ultimately negative [46], [74].

Task Content. Several studies reported the benefits of an inclusive design approach, which involves children, families, teachers and other related parties in the design phase. Inclusive design help adapt systems to the different needs and perceptions of individuals with ASD [80], [91], [92], [94], [98], [101], [103]. Participants with ASD were willing to customize the virtual environment in some studies [80], [97], [98], [104], [105]. The researchers stated that this was expected to have a positive effect on training of children with ASD by enabling identity expression. As an example, children showed willingness to customize the design of the virtual environment, such as adding animals to the outdoor scene in [97].

Meaningful virtual experiences that have a link to the real world provided better training in many studies [20], [83], [86], [100]. As a related practice, authors shared a good design principle of placing the users at their normal real-world height level in the virtual world, so that they see the virtual world from a height that is similar to their own height in the real world. Similarly, individuals exhibited more active participation when they were characterized with more engaged roles in the virtual world [80], [97]. Examples given for more engaged roles were tasks requiring leadership and conversation initiation. When users were portrayed as leaders in virtual world scenarios, they were more prone to act as a leader in subsequent real world interactions. Integrating fun into training provided motivation for individuals with ASD and yielded more engaging training [52]. Multiplayer interactions and story driven goals provided better transfer of trained tasks to the real world [106].

3.3 VR System

Controlling. Complex controlling inputs were stated to create frustration in many studies. Simple and intuitive controls were favored as a better design principle [48], [52], [74], [83], [100], [107]. Giving control on redundant aspects was observed to confuse the users. Limiting the controls on the redundant aspects such as camera rotation or volume level, or providing auto controls worked better. Researchers advised keeping the number of controlling keys as low as possible.

Commonly seen motor difficulties in individuals with ASD called for the use of less tiring input devices [74], [92], [100]. In [83], keyboard and mouse control were preferred over joystick and gamepad control. The authors observed difficulty especially in the usage of joystick. In a follow-up study, stickers on keyboard keys for visual reinforcement provided ease of use for children with ASD.

Other. Tethering the headset to the computer via cables was reported to create safety concerns [20], [83]. Use of non-tethered displays was advised by the researchers for individuals with ASD.

Embodied interaction that utilizes full body motions of the users rather than using only some limbs was stated to work better in terms of engagement for individuals with ASD according to the observations of the researchers [20], [78].

Using the technological tools in the users' naturalistic settings instead of bringing them to a specialized facility was stated to work better for individuals with ASD [104], [108].

As a final general guideline, providing variety in tasks, modes of information presentation and interactions was suggested by some studies [86], [99], [100]. Since autism is a wide, spectrum-based disorder, this kind of variety allows applications to be adapted to the different sensory needs of each individual. More commonly seen deficiencies across the spectrum, such as executive decisions and focusing, should be integrated overall. It may also be a good practice to preconfigure the tasks, information presentation methods, and interaction methods of the application and only present users with a simple interface and simple sensory outputs.

3.4 Comparative Studies

There are small number of comparative studies on the validity of VR and effects of some VR properties on training individuals with ASD. Mineo et al. studied engagement of individuals with ASD in four types of visual information presentation modes: animated video, video of self, video of a familiar person engaging with an immersive VR game, and exposure of self in an immersive VR game (the same game used for the video of a familiar person condition) [109]. In the self-exposure to VR condition, the users saw themselves in the VR game via video capturing and their movements impacted the actions in the virtual world. All methods were presented the user via a 20-inch display. To compare these four methods, the authors took into account gaze direction and vocalization as measures of engagement. The user study with 42 students indicated that the users showed interest in all four methods, but got engaged the most when they saw themselves on the screen in the immersive VR game. This condition yielded longer gaze durations and more vocalization.

Grynszpan et al. investigated the effect of output modalities of text, images, and synthetic speech voice on social dialogue understanding tasks [96]. The authors also studied effects of realistic and cartoonish visual modality on emotion recognition tasks. Educational software for both tasks was prepared. The first one was composed of dialogue understanding and the second one was built on top of the first one so that it included facial expressions supplementary to the dialogue. The first task was compared with a simple interface that contained only the absolutely necessary features presented with written text, and a multimodal interface that contained images, sound and voice synthesis. The aim of this task was to understand the contents of a dialogue. The second task was compared with an interface with text, synthetic speech and realistic face images that present expressive features, and an interface with text, synthetic speech and cartoonish face images that present more exaggerated expressive features. The aim of this task was to disambiguate a dialogue using facial expressions.

Results of a user study with ten children with ASD revealed that multimodal output had a negative effect on performance. The rich interface also yielded more difficulty in transfer of skills. The authors stated the possible reason behind this as the multiple simultaneous modes of information presentations' bringing complexity to the task at hand for individuals with ASD. This outcome concurs with other studies that indicate ASD individuals have difficulty in processing multiple stimuli concurrently [110]. The authors did not investigate the effects of these output modalities alone. They only compared text with a combination of text, images, sound and voice synthesis.

The cartoonish and real visual representation of faces did not have an impact on the performance. The authors stated that this might be due to users with ASDs' avoidance from eye contact and as an alternative they suggested using nonhuman characters in future studies. The tasks of the study were already designed to be complex for individuals with ASD. The dialogues included irony and other abstract language concepts that individuals with ASD are known to have difficulty with. This might also be the reason behind the poor performance in relating the facial expressions to the social context of the dialogues.

Newbutt investigated the self-representation of young people with ASD in virtual worlds through creation of avatars [104]. Participants were requested to fulfill a questionnaire about their preferences before taking part in the case studies. This questionnaire mainly included questions on video game habits and preferences on different video game elements. Young individuals with ASD stated preference for cartoonish avatar over a realistic photo of themselves or a 3D avatar character. Individuals with ASD stated preference for game devices that are social by nature (such as Nintendo DS and Wii) over conventional game devices (such as Xbox and PlayStation). Individuals with ASD stated preference for only hearing a person instead of both hearing and seeing them. Following, the participants were offered tools to customize their avatars. It was observed that participants with ASD showed willingness in being stakeholders in the virtual world through using the software and customizing their own avatars, which was interpreted as an indicator of increased sense of presence. It was observed that participants with ASD were more interested in customizing the body of the avatars than the face. The author pointed out that the fidelity of the avatar held limited relevance for the participants with ASD.

Newbutt also looked into the communication and interaction aspects of virtual worlds for young individuals with ASD in the same study. The author mainly examined the useful aspects of virtual worlds for communication and their usage by individuals with ASD. Participants with ASD preferred text chat based communication over gestures and body animations. As the content of the text communication were examined, it was found out that there were some inappropriate comments (with a mean of 22.14 percent).

Bekele et al. investigated the response of adolescents with Autism to different facial expressions in virtual reality environments [111]. The researchers collected eye tracking and physiological data to determine variations between different expressions and user groups. User study with ten adolescents with ASD and ten neurotypical adolescents indicated that there were differences in the way the two groups process and recognize emotional faces.

On a similar note, Wallace et al. explored whether children with ASD experienced immersive virtual environments different than typically developed children [91]. For this, two tests were performed in a CAVE-like environment: For the first test, participants rated their sense of presence in three different virtual scenarios, each supported by natural sound effects. For the second test, participants rated the enjoyment of watching a virtual character that behaves in either a socially desirable or undesirable fashion. The user study included ten children with ASD and 14 typically developed children. Both groups showed similar levels of presence and engagement in content, and both groups did not show any negative physiological responses to immersive virtual scenarios. Children with ASD rated the socially desirable and undesirable versions of the virtual character as equally attractive. Typically developed children rated the socially desirable version as more attractive than the socially undesirable version. This might be due to the lack of attention to social cues in some people with ASD.

The study suggests that children with ASD do not feel different levels of presence than their typically developed peers in immersive virtual environments and immersive virtual environments can create authentic social situations. The results of the surveys indicated promising results in transfer of the virtual experiences to real life. The results of this study should be interpreted in the context of the designed tasks though. Since the virtual environments did not include any interaction, it is difficult to conclude that children with ASD experience VR the same as their typically developed peers. On a related note, Newbutt et al. studied the effects of off the shelf software for Oculus Rift on individuals with ASD regarding sense of presence and immersion [42]. A user study with 29 individuals with ASD resulted in high presence scores and an enjoyable experience. On the contrary, Dautenhahn [20] and Rijn and Stappers [78] found that questions about the sense of being in the virtual environment might be interpreted differently by people with ASD.

Saiano et al. investigated the effects of interface type on acquisition of pedestrian skills via VR training by individuals with ASD [112]. The authors compared a gesture controlled version (Microsoft Kinect) and a gamepad controlled version of the same VR system. The results of a user study with dour individuals indicated that both interfaces provided effective learning however, gamepad was easier to use. On the other hand, gesture based systems tended to better transfer into real life as stated by parents.

Mei et al. explored effects of customizable avatars in virtual reality on user performance and user experience of adolescents with ASD [105]. The authors compared the differences with two versions of the same system: customizable virtual avatars and non-customizable virtual avatars. Results of the user study with 10 participants with high functioning ASD indicated that customizable virtual avatars yielded improved performance, more motivation and better user experience.

3.5 Summary

In this section, we presented design considerations that have been shared by previous studies in the literature.

We think that these guidelines have limited validity due to the following reasons: First and foremost, the studies primarily derived guidelines based on subjective observations by researchers, participants, families and teachers instead of performing comparative scientific studies. Second, these suggestions were mostly drawn from user studies that tested the effectiveness of VR in enhancing skills of children with ASD not focusing on the effects of different virtual reality properties on user experience. Third, the low number of comparative studies involved a small number of participants (mostly less than ten). Fourth, most of the studies were for children with ASD, making it unclear if the design considerations are applicable to adults with ASD as well. Fifth, these guidelines were highly dependent on the study tasks, which makes it questionable if the considerations would be applicable in other task settings. Sixth, most of these studies did not compare alternatives for the suggested considerations. As an example, a design guideline favoring the use of verbal instructions was not derived through comparisons with written, image based or animated instructions. The researchers only shared their observations on the verbal instructions' working well in the context of their study.

Thus, we cannot assess if these guidelines are overall good VR design practices for individuals with ASD. Nonetheless, some design guidelines were identified in a relatively large number of the examined studies. Hence, even though they were not based on data or comparison, we think that these common observations may be considered more reliable than others. Design guidelines and considerations that were shared by more than three studies are synthesized in Table 1.

Our systematic literature review indicated that although there are some useful design considerations that were shared by the previous studies, there are no well-established design guidelines in the literature for virtual reality applications targeting individuals with ASD that were found out by systematic studies. The existing studies agree on the positive acceptance of VR by the individuals with ASD and the potential of VR as a training tool. However, many studies also share the difficulty of making sure to achieve a design that serves the needs of this special population well, due to lack of well-established design guidelines. To benefit from this promising new technology for training individuals with ASD, more comparative studies that reveal reliable design principles are needed. Previous major literature review studies that examine VR applications for individuals with ASD also agree on the need for more controlled studies and data to reveal the best design principles for the needs of this special group of individuals [63], [73], [113].

4 VR Training Applications for Individuals with ASD

It seems reasonable to assume that one of the most important and valuable uses of virtual reality for individuals with autism is for training/targeted intervention. To identify the common characteristics of the previous works in this area and identify the future improvement areas, we performed a systematic literature review following the guidelines by Kitchenham et al. [76]. The same electronic resources that were listed in Section 3 were used in this search also. To identify the primary studies, the following criteria were applied:

Inclusion Criteria. • Any scientific publication that utilized virtual reality for training/targeted intervention of individuals with ASD (studies that aimed to improve some specific skills of participants via exposure to a virtual reality system).

Exclusion Criteria. • Scientific publications that aimed for other purposes such as entertainment. • Studies in a language other than English. • Multiple versions of the same study (in this case, the most complete paper was selected) • Self-publications (due to conflict of interest).

Search Strings. Virtual reality AND autism

Abbreviations/Synonyms. VR, ASD, Asperger's

Reference Manager. EndNote

To undertake a comprehensive research, we tried to keep the exclusion criteria as small as possible since we were aware of the small number of studies in this area from our previous studies. The search strategy was as follows: The electronic sources were scanned for all studies that met the criteria above. Then, the title and the abstracts of these studies were read. The studies were kept if they were related to training/targeted intervention of individuals with ASD using virtual reality. If not, the studies were discarded. Following, the selected studies were read thoroughly. The references from these studies were also checked for relevance and added to the selected primary studies if they were relevant. If an aspect of the study was not understood or was missing from the article, the corresponding author was contacted (for example if the type of virtual reality system was not clear or the tutorial method in was not specified). If no response was received in a month's duration, this aspect was referred as 'not specified' in our review. The studies were then scored for the quality assessment. Following the instructions of Khan et al. [114], we constructed a quality questionnaire based on ten issues regarding the study and reporting quality and then combined these two measures with different weights to get an overall study quality score. In the quality questionnaire, the following issues were assessed:

Quality of the Study. • Were the methods/VR system appropriate for investigating the research questions? • Were the data collection methods clearly described? • Were there enough participants with ASD? • Were there enough neurotypical participants as the control group? • Were the data analysis thorough and statistically strong? • Were the study questions answered?

Reporting Quality. • Were the methods clearly reported? • Were there enough references? • Was the paper well organized? • Were there visual aids (pictures/flowcharts) that explained the system?

All questions were answered as yes/partially/no, which were then translated into scores of 1/0.5/0 respectively. The quality of the study was given more weight (78 percent) whereas the reporting quality was given less weight (22 percent). To achieve a maximum overall score of 100, the following multipliers were then obtained: 14 for the questions of the quality of the study, 4 for the questions of the reporting quality. The overall score was then obtained by multiplying the scores of each question with their corresponding multiplier and adding all together.

In addition to the scoring, several distinctive data were extracted from the primary studies such as: the source, VR system type, number of participants, ASD severity, contributions and results. The aim of the data extraction was to find out if there are common patterns in the design choices of the previous studies. In the selection of this extracted data, the criteria were as follows: • Being an important design consideration for VR systems targeting neurotypical individuals (such as the type of the system, tasks involved, number of participants, and contributions). • Being relevant to the characteristics of individuals with ASD mentioned in Section 1 (such as method of instructions, visual fidelity, level of dynamism in the virtual environment, and existence of an avatar). These data were then synthesized in a table format (in Table 2, which will be revisited later). The primary studies were sorted in the table according to their overall quality score.

We propose a taxonomy that is based on the type of the VR system: immersive or regular, and the type of skill the study aims to train users on: social skills, life skills and safety skills since they seem to be the most distinctive generic features that divides the works into clusters. As discussed previously, immersive VR is a type of VR in which the user is surrounded by the images via a head mounted display or CAVE-like projections and the virtual world is rendered based on the head movements of the user. Regular VR systems usually use computer monitors or TVs as displays that do not incorporate head movements of the user into rendering the virtual worlds. Social skills mainly encompass conversational and emotional expression understanding. Life skills are skills that help users in their everyday lives. It may be argued that social skills are a subset of life skills. We separated social skills from other life skills since most previous VR training systems focused on social skills whereas a limited number focused on other life skills such as driving and using one's imagination. Safety skills are mainly about how to respond appropriately during an emergency, such as a tornado or fire, and how to cross a street safely. Previous studies are presented according to their taxonomy category in Fig. 1.

In this section, we present some of the key works in the area of using VR for training individuals with ASD.

4.1 Immersive VR Training Applications for Individuals with ASD

In this subsection, we present training applications that utilize immersive virtual reality for training individuals with ASD on social skills, life skills and safety skills.

Social Skills Training. Lorenzo et al. developed an immersive virtual reality system for learning social skills and executive decision making for children with ASD [85]. Gaze and face expressions of the users were collected and used for evaluation and adaptation of the system according to the user's needs. The system offered several customizable task scenarios that were focused on school and home-based social activities. The study with 20 participants with ASD was performed. Social competences and executive functions of the participants with ASD have improved and the results of the study were in favor of employing immersive VR applications for educational interventions of children with ASD. Transfer of learned skills to classroom was also observed by the tutors of the participants. Researchers observed that the participants showed engagement with the virtual avatars and were motivated by them.

Matsentidou and Poullis also worked on an immersive VR application for training children with ASD on social skills [115]. The system presented social stories in an immersive VR CAVE-like environment. The researchers performed a user study with neurotypical participants. Neurotypical participants were able to use the system and showed improvement in social situation handling skills. No user study with individuals with ASD was performed due to lack of volunteer participants with ASD. Although the researchers developed a complex VR system with state of the art components, it provides no evidence the system would work well for children with ASD.

Cai et al. developed a virtual dolphinarium for training children with ASD on social skills [116]. The users acted as dolphin trainers and were trained on non-verbal communication skills through hand gestures with virtual dolphins.

TABLE 2
Previous Studies on Training Individuals with ASD Using VR, Summarized According to Several Properties

Ref	Sc	Skill	VR System	Tutorial Method	VF	Cr	Dyn	Tasks	PoV	AP	TA	PD	ASD Severity/IQ	Part	Contribution/Results
[85]	79	Social and executive decision making	Projections on an L shaped display, 3D glasses	Virtual avatar	Mid	Mid	Mid	Talking with virtual avatars, manipulating and interacting with virtual objects	1st	No	Children	No	Asperger's Syndrome	20 ASD	Improvement in social skills and executive functions of the participants was reported. Transfer of learned skills to classroom was observed.
[132]	75	Job interviewing	Computer	Human	Mid	Low	Low	Talking and selecting among options	1st	No	Adults	No	SRS-2 μ: 67.4	26 ASD	The VR system was proven to be an effective tool for improving job interview skills of individuals with ASD. Participants who used the VR system showed more improvement than traditionally trained participants.
[127]	73	Social	Computer	Virtual avatar	High	Mid	Mid	Navigation, talking with virtual avatars and interaction with virtual objects	3rd	Yes	Young adults	No	FSIQ μ: 111.88, ADOS μ: 8.25	8 ASD	Improvement in social and occupational functioning of the participants was reported.
[118]	72	Fear/ phobia overcoming	360° CAVE environment	Human	High	Mid	High	No interaction for the participant, instructor controlling	1st	No	Children	No	SCQ range: 13 to 31	9 ASD	Participants were able to tackle their phobia after using the system. Provided evidence that VR and Cognitive Behavior Therapy can be used as a treatment tool for overcoming phobia.
[123]	70	Social	Computer	Human	Low	Grad. inc.	Grad. inc.	Simple navigation and interaction with virtual objects	1st	No	Adolescents		VIQ μ: 81.9, PIQ μ: 87.1, FSIQ μ: 83.1	7 ASD	Improvement in social skills of the participants was reported.
[133]	68	Safe street-crossing	Computer	Human	Low	Mid	Mid	Rotating the screen and moving forward	3rd	Yes	Children	No	Moderate to severe (CARS μ: 40)	6 AS- 6 NT	VR training enabled participants with ASD learn safe street crossing skills. Skills transferred to real life for half of the participants with ASD.
[124]	66	Social	Computer	Virtual avatar	Mid	Mid	Low	Selecting among options	1st	No	Adolescents	Yes	High functioning (PPVT μ: 120.38, SCQ μ: 14.88)	8 ASD	Promising results in terms of providing improvement in social skills of participants with a customized adaptive VR training system. The addition of gaze tracking based adaptation on top of performance metrics based adaptation provided better training.
[82]	65	Social	Computer	Human and virtual avatar	Mid	Mid	Mid	Answering questions, making selections, communicating written and verbally	3rd	Yes	Children	No	FSIQ μ: 102.33, PIQ μ: 102, VIQ μ: 102.33	3 ASD	Improvement in reciprocal social behaviors of the participants was observed.
[116]	65	Non-verbal communication	Projections on a surrounding curtain	Human	High	Mid	Mid	Performing hand gestures to communicate with virtual dolphins	1st	No	Children	No	Mild to very severe (NIQ μ: 83, AQ μ: 103)	15 ASD	Most participants were engaged. Some showed learning. Some on the low functioning side were overwhelmed and unable to learn.
[122]	63	Safe road crossing	Projection on a large display	Human	High	Mid	Low	Following signs, observing the objects and simple navigation	1st	No	Adults	No	Mild (VIQ μ: 40, PIQ μ: 83, FSIQ μ: 42)	7 ASD	Improvement in navigation skills, no improvement in safe street crossing skills in VR. Improvement in real life street crossing skills.
[126]	61	Social problem solving	Computer	Virtual avatar, text, audio	Mid	Mid	Low	Simple navigation, interaction with objects and answering multiple choice problems	3rd	Yes	Children	No	N/A	N/A	Teachers found the application useful. No user study was conducted.
[97]	59	Social	Computer	Virtual avatar	Mid	High	High	Navigation, talking with virtual avatars and interaction with virtual objects	3rd	Yes	Children	No	Asperger's Syndrome	4 ASD	Improvement in interaction and communication performance of the participants was reported. Observations on design considerations were shared.
[121]	56	Safe road crossing	CAVE projection, 3D glasses	Human	High	Mid	Mid	Observing the objects and simple navigation	1st	No	Children	No	Not Specified	6 ASD	Most participants were able to learn the skill and transfer it to real life.
[65]	50	Imaginative		Human	Mid	Mid	Mid	Selecting among options	1st	No	Children	No	Leiter IQ μ: 89	2 ASD	Pretending and imaginative abilities of the participants were advanced after using the VR system.

TABLE 2
(*Continued*)

Ref	Sc	Skill	VR System	Tutorial Method	VF	Cr	Dyn	Tasks	PoV	AP	TA	PD	ASD Severity/IQ	Part	Contribution/Results
			Computer with touch screen												
[117]	49	Social	HMD and computer	Human	Mid	Low	Mid	Minimal interaction (dragging coins into box, selecting answers)	1st	No	Children	No	FSIQ μ: 82, PIQ μ: 82.33, VIQ μ: 79.33	3 ASD	Improvement in social behaviors of the participants. Results suggest that the VR system is promising as a training environment for social skills.
[115]	47	Social	CAVE projection, 3D glasses	Human	Mid	Low	Mid	Navigation and interaction with virtual objects	1st	Only Hands	Children	No	N/A	12 NT	Participants were able to use the system and showed improvement in social situation handling skills. No user study with individuals with ASD was performed.
[12]	45	Safe street-crossing	HMD and computer	Human	Low	Low	Low	Observing the objects and simple navigation	1st	No	Children	No	Mild to Moderate (CARS μ: 35.25)	2 ASD	Acceptance of VR was noticed. Indications of immersion and generalization of learned skills were observed.
[64]	43	Fire and tornado safety	Computer	Human	No Info	No Info	No Info	Navigation and clicking on doors	No Info	No Info	Children	No	Verbal communication and computer operation	8 ASD	VR training worked as effective as real world training and provided faster learning.
[119]	43	Travelling	HMD and computer	Human	High	Mid	Mid	Going to predefined places by walking and taking a bus.	1st	No	Adults	No	Not Specified	5 ASD - 5 NT	Acceptance of VR. Promising in providing travel training.
[128]	41	Everyday	Computer	Human	High	Low	Low	Low functioning: only selection. High functioning: navigation and interaction with objects.	1st	No	Children	No	Different levels of functioning	20 ASD	Formative pilot studies suggested that the system would be useful in training everyday tasks. No data of the pilot study was shared and no follow up evaluative user study was conducted.
[87]	38	Social	Computer	Human	Mid	Mid	High	Selecting among options	1st	No	Adolescents	No	N/A	No number	The system did not support active participation of the user. Heavily based on verbal and written statements. No user study was conducted.
[130]	36	Driving	Computer	Animated with audio	Mid	High	High	Realistic car driving interaction (with steering wheel, pedals and gears)	1st	No	Adolescents	Yes	N/A	4 NT	A custom VR driving training system that can understand various performance measures in real time such as level of anxiety and gaze direction. Results indicated differences in performance and behaviors in neurotypical and ASD participants.
[48]	34	Everyday	Computer	Pictographs and audio	Low	Mid	Low	Simple navigation and interaction with virtual objects	1st	No	Children	No	Not provided	No number	Teachers found the application useful.
[120]	29	Generic competencies	Projections on a table surface	Human	Mid	Low	Low	Pointing to objects, selections. Object recognition, and association with key-words.	1st	No	Children	No	N/A	N/A	Demonstration to psychologists and teachers indicated that the tool was promising. No user study was conducted.

- Ref: Reference
- Sc: Score (Out of 100)
- VF: Visual Fidelity
- Cr: Crowdedness
- Dyn: Dynamism
- PoV: Point of View (1st or 3rd Person)
- AP: Avatar Presence
- TA: Target Audience
- PD: Physiological Data?
- Part: Participants
- Grad. inc: Gradually increasing
- CARS: Childhood Autism Rating Scale [134]
- SCQ: Social Communication Questionnaire [135]
- FSIQ: Full Scale IQ [136]
- PIQ: Performance IQ [136]
- VIQ: Verbal IQ [136]
- Leiter IQ: [137]
- PPVT: Peabody Picture Vocabulary Test [138]
- ADOS: Autism Diagnostic Observation Schedule [139]
- NIQ: Nonverbal Intelligence Quotient [140]
- AQ: Autism Quotient [141]

	Social Skills	Life Skills	Safety Skills
Regular VR	[82], [87], [97], [123], [124], [126], [127]	[48], [65], [128], [130], [132]	[64], [133]
Immersive VR	[85], [115], [116], [117]	[118], [119], [120]	[12], [121], [122]

Fig. 1. Taxonomy of studies on VR training for individuals with ASD.

The system was implemented in a large room with a 320° curved screen along with a five panel projection system. Children were requested to perform gestures such as greeting via hand waving and cueing the dolphin to spin via hand raising. A pilot user study with 15 children with ASD indicated that most of the participants were interested in and engaged with the system. Learning was observed in some participants. However, some participants with low functioning ASD were overwhelmed by the VR experience and were unable to learn.

In a recent study, Cheng et al. used immersive virtual environments to enhance the social skills of children with ASD [117]. In the study, non-verbal communication, social initiations and social cognition aspects of social skills were explored. The users answered multiple choice questions assessing social skills using a mouse in two virtual environments: bus stop and classroom. They viewed the environment through an HMD. Preliminary results of the tests by three participants showed that social behaviors of the participants were improved after the training. This indicated that the system was promising as an effective learning environment for social skills for children with ASD.

Life Skills Training. Maskey et al. focused on using immersive virtual reality along with cognitive behavior therapy to reduce some phobias and fears, such as crowded buses and pigeons, in young people with ASD [118]. The users entered into a CAVE-like environment with an accompanying therapist. The therapist first presented the users with relaxing scenes. After the users stated that they were ready to proceed, the therapist presented the users with immersive virtual environments that were designed beforehand by the therapists to specifically target the user's fear/phobia. The users did not control any aspect of the virtual environment, but were able to navigate in the real room if they wished, although their movements had no effect on the virtual world. Other than that, participants were also free to talk and observe during the sessions. The results showed that the combination of VR and cognitive behavior therapy is very promising in effective treatment of specific phobia and fears in young individuals with ASD.

Bernardes et al. developed a virtual reality serious game that aimed to train users with ASD on travel skills such as using buses as a mean of transportation [119]. A preliminary study was conducted with five individuals with ASD and five neurotypical individuals. The results indicated that the system was promising in terms of providing travel skills training and was accepted by the participants.

Lakshmiprabha et al. developed a system to explore the use of augmented reality and virtual reality for training children with ASD on learning new pictures, objects and key words [120]. The researchers utilized applied behavior analysis techniques for teaching. The system projects images on a table surface and allows for selection interaction with those projections. A prototype was developed and demonstrations to the ASD psychologists and teachers were promising in terms of providing children with ASD with the following skills: generic competencies, associating keywords with pictures, and identifying objects.

Safety Skills Training. Strickland et al. conducted one of the earliest studies exploring the use of VR for teaching safe street crossing skills to children [12]. The users needed to watch and identify moving cars and traffic signs, and follow images that were created by a 3D mouse. The users had difficulty in using the controller; hence the researchers conducted the study with verbal responses and untracked real walking motion of the participants. A case study with two children with ASD showed promising observations. The children immersed themselves in the virtual worlds and accepted using the head mounted display, even if it was big, heavy, early model headset. Children were able to use the learned skills in three different virtual environments, indicating possible generalization. One user appeared to understand the interaction mechanics of virtual reality while the other user treated the HMD more like a typical computer display, trying to only watch and point to it.

In a recent study, Tzanavari et al. developed an immersive CAVE based VR system for training children with ASD on safe pedestrian crossing skills [121]. The system included projections on four surrounding walls. The users wore 3D stereoscopic glasses and used an Xbox controller for interaction and navigation. Users needed to follow six steps to successfully cross the road. User study results with six children with Autism diagnosis indicated that after four sessions of training on four separate days of using the VR system, most children were able to learn the skill and transfer it to the real world. Real world skill transfer was verified by a road-crossing test in the real world with an accompanying parent or educator for safety reasons.

Saiano et al. investigated the effectiveness of a virtual reality tool for the acquisition of safe street crossing and path following skills in adults with ASD [122]. The system included projections on a 2 m by 23m screen and rendering based on a first person perspective. Full body movements of the user were captured via Microsoft Kinec. The users needed to perform gestures to follow road signs and to safely cross streets. Six individuals with ASD participated in a user study. Results indicated improvement in navigation skills however no improvement in safe street crossing skills in VR. A follow up interview revealed that the caregivers observed improvements in the users' street crossing skills in real life.

4.2 Regular (Non-Immersive) VR Training Applications for Individuals with ASD

In this subsection, we present training applications that utilize regular (non-immersive) virtual reality systems for training individuals with ASD on social skills, life skills and safety skills.

Social Skills Training. Mitchell et al. utilized a non-immersive virtual reality system to train teenagers with ASD on social skills in public settings [123]. The social skills targeted were finding a place to sit in a crowded environment and asking appropriate questions. A user study with seven participants with ASD was performed. After training with the VR system, the users were requested to answer questions about real life videos of situations that were similar to the trained ones. Results revealed that the social skills of the participants were improved after training with the system. The system turned out to be promising in terms of using VR as a training tool for social skills. The system did not have high visual fidelity but still provided effective training. The study contributed to the findings that VR could be an effective tool for individuals with ASD to train on social skills.

Ehrlich and Miller developed a non-immersive VR system for teaching social skills to adolescents with ASD [87]. In the system, several real world situations that challenge children with ASD took place in different virtual environments. Although the system was rich in scenarios and environments, the potential of virtual environments in engaging the user actively was not fully utilized. In the background, animated scenes taking place in a virtual environment were presented. Layered on top of the environment was a question (with multiple choice answers) presented to users both written and verbally. The user was expected to make a selection. Based on that selection, the system gave written and verbal feedback. The virtual world acted as a background scene that looped. The system heavily relied on written and verbal statements, which is questionable as an effective training method for individuals with ASD considering suggested practices of ASD experts. Since the authors did not conduct a user study, it is difficult to make any conclusions about the effectiveness of the system in training users with ASD.

Cheng and Ye examined the use of non-immersive VR for improving social interaction of children with ASD [82]. Their system included answering questions related to some animated social situations and allowed for written and verbal communication with the instructor. The user and the instructor were represented by virtual avatars and both participated in VR training, by controlling their virtual avatars and communicating with each other. The user was able to select different facial expressions for their virtual avatar while communicating with the instructor. The context of the tasks involved understanding verbal and non-verbal communication with virtual avatars. The pilot study results of three participants suggested improvement in reciprocal social behaviors such as appropriate manners, eye contact and maintaining conversation. However, low number of participants makes it difficult to generalize the outcomes.

Lahiri et al. developed a non-immersive VR system for social communication skills training of individuals with ASD [124]. Social communication tasks were offered in training. Virtual avatars told personal stories that were supported by background virtual world presentations. The users maintained virtual conversations with the avatars by selecting from the provided options. The system was adaptive based on gaze tracking data. Gaze direction and performance metrics of the users were measured and the difficulty level of the questions was adapted accordingly. This enabled a customized session for each user, based on their parameters. The authors compared the usability of the gaze direction and performance metrics based adaptive system with the adaptive system that was based on only performance metrics. The details of the adaptation based on user parameters were discussed in a follow-up study [125]. The results revealed more improvement with the gaze direction and performance metrics based adaptive system. The system lacked active participation of the user. The participation of the user was limited to only making selections among given options. For a more realistic training, utilizing speech recognition may be considered.

Volioti et al. investigated use of virtual learning environments in improving social skills of children with ASD [126]. The system included learning via social stories. Pilot evaluation of the system indicated that it was promising in terms of improving social problem solving skills of children with ASD. The system was implemented on a desktop computer and users were expected to complete tasks such as interacting with objects, simple navigation, choosing the chair with their name on it, answering multiple choice social questions. A pilot study was performed with 43 special education teachers. The teachers completed questionnaires assessing the usability of the application. Results of the pilot study indicated that the virtual reality application was promising in terms of teaching social problem solving skills to children with ASD.

Some researchers utilized Second Life in their studies. Second Life is a popular web based game in which users can customize a virtual avatar that represents themselves or any other desired human figure [37]. The system also supports verbal and voice based communication of users through virtual avatars. Since the multi-player game allows for high scenario, environment and character customization, some studies adopted Second Life as their VR training system.

Kandalaft et al. explored use of Social Life as a non-immersive VR social skills training application aiming at enhancing social skills of young adults with ASD [127]. A protected island that was not accessible by outside players was used in the study. Avatars were designed to resemble the real life appearance of the users and the trainers. The system trained the users on several social scenarios such as job interviews, meeting new people and negotiating social decisions. The users were requested to talk to virtual characters and interact with virtual objects and avatars to complete these social scenarios. A real life tutor accompanied the user in the role of a virtual avatar and provided continuous feedback during the training. A user study with eight individuals with ASD revealed enhancement in social skills of the participants; mainly in emotion recognition from faces and voice, and recognizing and responding to other's thoughts. The system did not reportedly improve conversational skills of participants according to the user study results. However, six month follow up surveys indicated that the participants perceived an improvement in their own conversational skills after the VR training. The follow up surveys also indicated generalization and transfer of the learned skills. The VR system was found feasible as a social skills training tool. The system enabled training on complex social scenarios. As a downside, requiring a real life tutor actively participating in the training sessions does not fully utilize the scalability advantage of VR applications.

Another study on social skills training for individuals with ASD in Second Life was performed by Ke and Im [97]. The tasks included recognition of body gestures and facial expressions of virtual characters, maintaining conversation and initiating interactions. A user study with four participants was performed. The participants demonstrated improvement in interaction and communication performance. Other findings on design considerations were also reported. These were mainly on the importance of portraying the children as a leader in the virtual world to encourage their leadership skills, allowing for children's customization of virtual world and demonstration of the tasks by a virtual character for better learning. The study contributed to the previous findings on the viability of VR as a training tool for individuals with ASD.

Life Skills Training. Charitos et al. developed a VR system for training children on organizational skills for everyday tasks [128]. The system presented several everyday tasks such as washing hands and eating. The user needed to follow a virtual character inside a house while the virtual character performed these everyday tasks. Different from the other works, the system catered to two levels of autism: low-level and high level. In the low level mode, the user was only expected to make some simple selections whereas in high level mode, the user participated more actively. The authors performed in-house pilot studies with children with ASD while developing the system but did not share any data related to these studies. No follow up user study was performed. Hence, it is difficult to comment on the reaction of the users and the effectiveness of the system.

Lanyi et al. developed a VR system for training children with ASD in daily life skills of shopping, clothing and public transport [48]. The system was low in degree of interaction provided and was not designed with the aim of being highly immersive in terms of visuals. Although no formal user study was performed, some students with ASD tried the system with accompanying observing teachers (no number was specified). Teachers stated that they found the application useful. However, no user study results supported this observation on the effectiveness of the system.

Herrera et al. developed a VR system for imagination and abstract conceptualization training of individuals with ASD [65]. The authors discussed the design considerations for the mentioned training system in [129]. The system allowed for manipulation and transformation of properties of virtual objects to train children on size, position, quantity and visual concepts. Some other concepts such as time and seasons were also taught with the help of different conceptualizations. The children could play games of imitation and learn about different usages of different objects (using a banana as a telephone), to improve their imagination skills. A case study with two children with ASD showed promising results in the advancement of pretending and imagination abilities of the participants. Since the participant number is very low, validity of the results remains questionable as with the most of the studies.

Wade et al. utilized a custom and adaptive virtual reality driving environment to train individuals with ASD on driving skills [130]. The system collected real time physiological data and tracked eye movements of the users. The user needed to drive to a destination while encountering other vehicles and obeying traffic rules. The difficulty level of the tasks was changed on the fly based on the physiological data, eye tracking data and the trainee performance, to accommodate for possible changes in the stress levels of individuals with ASD while acquiring a new skill. Details on adaptation of the system based on user parameters were shared in [131]. The user study with a small group of participants indicated that the system was sensitive in detecting subtle differences such as level of anxiety and gaze direction between participants with ASD and neurotypical participants. Although individuals with ASD experienced higher number of failures as compared to neurotypical individuals, the study implied that the VR system was promising in providing customized driving training for individuals with ASD.

Smith et al. used an immersive virtual reality system for job interview training of individuals with ASD [132]. The system consisted of a desktop simulation of job interviews with virtual people. The system provided speech recognition with prerecorded questions to create realistic job interview scenarios. The system provided trainees with real time feedback. The users were required to answer questions either using speech recognition or by mouse selection. The system used supplementary written and visual based e-learning materials to improve trainee performance during job interviews. The VR training system provided more improvement in job interviewing skills of the participants with ASD as compared to the participants with ASD who were trained using conventional methods.

Safety Skills Training. Self et al. utilized a VR system to teach children with ASD safety skills related to fires and tornados [64]. The tasks were designed so that the users needed to find their way through the emergency signed doors to exit a building during an emergency. Research team members explained the directions for each task to be performed in the VR to the participants beforehand. Visual prompts were provided by the research team members if the user had difficulty in understanding the verbal directions. The participants were trained on the two safety skills using either a conventional integrated visual training method or virtual reality. Both methods were successful in teaching and transferring the safety skills, but VR was reported to provide faster learning and better generalization of the learned skill as compared to the conventional training method.

Josman et al. studied the effectiveness of virtual reality in teaching safe street-crossing skills to children and adolescents with ASD [133]. The users controlled an avatar in a desktop virtual environment and tried to avoid cars while crossing a street. The aim of the study was to find out if VR was effective in teaching the children with ASD safe street crossing skills and if those skills were transferrable to real life. The results showed that the VR system was successful in teaching the users with ASD safe street-crossing skills and transfer to real life skills was observed.

4.3 Summary

The data extracted from these studies are synthesized in Table 2. The studies are sorted according to their overall quality score.

To answer our second research question, we examined Table 2. It can be observed that number of immersive VR studies is lower (40 percent) in comparison to number of regular VR studies (60 percent). This might be due to the higher cost and more difficult embracement of immersive VR systems as compared to the more prevalent computer systems in the previous years. Most of the studies targeted children with ASD whereas very few studies targeted adults with ASD (only 3 out of 24 studies).

Most of the studies concentrated on training individuals with ASD on social skills (%46). This concurs with the findings of [52], on which individuals with ASD and their parents were interviewed on which type of technology they would benefit from. Around 42 percent stated social and communication skills. Most of the studies were for medium to high functioning individuals with ASD. This makes it questionable that the implications of these studies are applicable to the lower parts of the autism spectrum.

Most of the studies (70 percent) used humans for tutorials (a human tutor explained the user how to use the system and what to do in the virtual reality application). Many studies (50 percent) used medium level of visual fidelity, medium levels of crowdedness (58 percent), medium level of dynamism (42 percent), 1st person point of view (75 percent), no avatar (75 percent). Most of the studies (91 percent) did not utilize physiological data such as stress signals.

The previous studies agree on the promising potential effective usage of VR in training individuals with ASD. However, user studies of most of the studies included only a small group of participants with ASD (7 on average). This yielded weak results in terms of statistical significance, if there were statistical analysis at all. This effected the overall scores of the studies in our literature review negatively (the highest score was 79 whereas the maximum possible score was 100).

The low number of participants was mainly attributed to the difficulty the researchers had in finding volunteer participants. For mobile systems such as computer based VR targeting children with ASD, finding participants was a bit easier since they were able to visit special schools of these children. For stationary systems such as CAVE environments or motion tracking based systems, the participants needed to come to the facility and this yielded fewer participants.

5 Future Research Considerations

VR training for people with disabilities is an emerging area in its early stages. Hence studies do not include well established results that provide statistically reliable data due to the low number of participants observed in many studies. This is mainly because of the target audience's being a special group that is rarer than typically developed individuals and autism's being a spectrum based disorder making it difficult to put boundaries on characterizing individuals.

Many studies assessed the potential use of VR for training individuals with ASD and reported positive results. The research to date included many case studies with important observations and preliminary results. However, lack of comparison studies makes it difficult to draw conclusions upon the preferences of this special audience group. Many studies consisted of developing a system that the researchers thought would serve best to the needs of individuals with ASD, and looking into its effects in terms of the main goal on a small group of users with ASD, if any.

More comparison studies designed towards the investigation of VR properties and tested by a significant number of participants would help next generation VR training applications for individuals with ASD in providing more comfortable and effective experiences. Possible collaborations with institutions providing service to individuals with ASD might help in finding more participants for future studies.

It is also important to note that most of the previous studies explored the use of computer based VR systems for training applications catering to individuals with ASD. Among the studies that included immersive VR systems, many used old generation HMD's compared to the today's technology. Hence, more studies exploring ways of utilizing new generation highly immersive VR for training individuals with ASD might provide valuable insight.

The literature review on the virtual reality systems with the aim of training/targeted intervention revealed that most of the studies focused on training users with ASD on social skills. Although it seems reasonable since social skills are important in life and deficiency in social skills are a common attribute of ASD, there is a lack of training/targeted intervention applications in other areas that could improve quality of lives of individuals with ASD such as vocational skills.

It would be important to find out effects of several VR properties on training individuals with ASD with VR systems. As examples, effects of different information presentation methods, different levels of visual fidelity (especially low and high since most of the previous studies utilized medium levels), output modalities, different levels of dynamism and crowdedness of the virtual environments could be explored. Effects of 1st person and 3rd person view, presence of virtual avatar, effects of avatar's appearance on users and effects of incorporating personal attributes of the user into the virtual world (such as clothing, hair color and model, and general physical appearance) would also reveal insight into better virtual reality experiences for individuals with ASD.

Generalization (transfer) of the learnt skills in VR to real life is another important area that would be explored. If the researchers could identify the factors that improve the rate of generalization (such as increased/decreased visual fidelity or more/less number of virtual environments), future VR applications can apply these principles, which would result in better quality training of individuals with ASD.

Finally, since autism is a spectrum based disorder and it is difficult to characterize the whole population with common characteristics; more studies that focus on the lower parts of the spectrum are needed. In the long run, design guidelines that are based on the severity of autism (low, medium and high functioning) would be valuable in meeting the needs of the different parts of the spectrum.

To sum up, a well-established design literature based on the perspective of users with different levels of ASD on VR applications would serve as a valuable repository for future applications, helping in producing a better picture and making the next applications better cater to the needs of individuals with ASD.

6 Conclusion

In this paper, we discussed the design considerations of virtual reality applications targeting individuals with ASD and examined the previous works on training individuals with ASD using virtual reality. Since characteristics of this population are different than neurotypical individuals, building applications for individuals with ASD offers new challenges and design issues. To date, several studies have explored the potential of VR as a training tool for individuals with ASD. Almost all studies agreed on VR's being a suitable tool for this purpose. Researchers made observations during the user study sessions of these studies and shared lessons learned and design practices based on these observations. In this paper, we present and discuss these shared design guidelines that were extracted with a systematic literature review. Considering that the guidelines accumulated in the literature so far are not based on strong data and comparative studies, but were obtained only by observation of small groups of users; we think that more studies are needed to build a well-established resource for design principles on developing virtual reality applications for individuals with ASD.

We also present a systematic literature review of virtual reality studies that aim at training/targeted intervention of individuals with ASD. Based on this review, we classify the studies according to a new taxonomy. Our taxonomy is based on type of the VR system: immersive (HMD or CAVE based) or regular (computer based), and type of skills the user is trained on: social, life and safety skills. The taxonomy mainly revealed that there are few number of studies that utilized highly immersive new generation VR systems and that concentrated on skills other than the social skills.

While VR is an exciting and promising new area, especially for training/targeted intervention of individuals with ASD, more comparison studies and reliable data are needed to identify benefits of different VR methods and properties, and leverage the future studies and systems. We hope that the literature reviews and their implications that are presented in this paper give insight and motivation to future studies for investigating how to design and develop better VR experiences for individuals with ASD and in the long run this population's getting more benefits from these VR experiences.

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